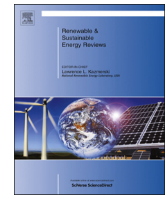
Renewable and Sustainable Energy Reviews 37 (2014) 348–359

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



On the competitiveness of electric driving in France: Impact of driving patterns

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A R T I C L E I N F O

Article history:
Received 25 July 2012
Received in revised form
18 March 2014
Accepted 27 April 2014
Available online 2 June 2014

Keywords:
Electric vehicle
Hybrid electric vehicle
Fuel Cell Electric Vehicle
Battery range
Driving patterns
Range anxiety
Electric driving distance

A B S T R A C T

The environmental issues in the transport sector are numerous and CO_2 capture is not even plausible for vehicles at the moment. This report describes a number of different emergent power train technologies (ICE, BEV, PHEV, FCEV) before providing an inter-comparison of these technologies within a technical and economic context.

The economical benefits are discussed in terms of the "Difference of Total Cost of Ownership" (DTCO) and take: electric driving distances, energy (fuel, electricity, hydrogen) prices, batteries and fuel cells costs. To simulate electric driving distances, the model uses several functional parameters such as the battery range and the 'range anxiety' based on the assumption of one recharge per day. The potential electric driving distances are evaluated according to the segmentation statistics of daily trips.

The results show the yearly mileages, as well as the range and cost of batteries and fuel cells, together with their relative impact on the DTCO and on the competitiveness of electric vehicles. The price of electric vehicles remains high with strong dependency on the battery's capacity, but the benefits in terms of fuel cost savings can be considerable. The price of electricity is currently noticeably lower than petroleum-based fuels, which balances the high costs of the batteries. 50% or more of LDV yearly mileages can be electric-driven, even for limited battery ranges (ca. under 50 km). There are stakes for the battery costs (competitiveness under €215/kWh) and lifetimes, while the low battery ranges (100 km in our case) provide the best margins.

As regards FCEVs, the hydrogen target price at the pump should be achievable (less than €6.5/kg) with reasonable gasoline prices (€1.7/liter at the pump) and fuel cell costs (€20/kW). CO_2 taxes and ICE efficiency gains will lead to opposite impacts of the H_2 target prices at the pump.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.04.056
1364-0321/

1. Introduction

In 2010, the IEA Energy Technology Perspective [1] defined reduction quotas for the major CO_2-emitting sectors, in particular the building, transport, industry and power generation sectors. With regard to the BLUE Map scenario, the power generation sector is the most concerned by these reductions, together with the transport sector. Compared with the baseline scenario, more than a 50% reduction is expected in 2050 by means of plug-in hybrid, electric or fuel-cell vehicles. Passenger road usage represents about 60–70% of all CO_2 emissions in the transport sector. This means that even with a 30% to 50% increase in the fuel economy for Internal Combustion Engines, conventional vehicles alone are unable to achieve the European Union's CO_2 reduction goal for 2050 [2], especially as CO_2 capture is not even considered as a viable solution for the moment. With the soaring price of oil, energy dependence has long become a crucial issue for countless countries worldwide. Global transportation and fossil fuels are inextricably linked. More than 60% of the 87 million barrels of oil is consumed every day by the world's transportation system, while liquid fossil fuels account for more than 96% of the current energy supply to the transport sector. Within the transport sector (Fig. 1), road transport accounts for more than 70% of the total transport energy consumption, which represents 52% for light-duty vehicles (LDVs) [3].

Data from the IEA BLUE Map scenario shows that Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs) will provide a 30% reduction in CO_2 emissions by 2050 for LDVs,[1] based on the assumption of 20 million EVs/PHEVs and Fuel Cell Vehicles by 2020.[2] Fig. 2 shows that the market share of electrified vehicles should grow after 2015: the deployment of gasoline vehicles will decrease, thus paving the way for the massive deployment of electric and hydrogen fuel cell vehicles after a 'hybrid vehicle' transition period [4].

From a strict technological viewpoint, it is now obvious that electric mobility has been growing strongly for 5 to 10 years. Available literature already considers fuel-cell and battery vehicles as competing or combined systems, vs. Internal Combustion Engine (ICE) vehicles. This is true from both an experimental and an economic perspective. This complex situation may put many technologies and possible combinations at stake: BEVs, PHEVs and FCEVs are the most frequently mentioned for comparison with ICE vehicles. While electric motors are generally used in FCEVs and BEVs, the architecture (in series or in parallel) of PHEVs determines the choice of motor. Thermal engines (ICEs) are generally employed in HEVs combined with an auxiliary electric motor; they are only refilled with gasoline (see Fig. 3 [5]). Electric power-trains are 2 or 3 times more fuel-efficient than Internal Combustion Engines (ICEs).

Otherwise, pure ICE vehicles remain promising solutions as regards the recent important progress in efficiency. The authors also have their own opinion about various technologies that can influence the choice of assumptions and the conclusions.

This paper raises a number of questions: is a techno-economic approach the only way to analyze future mobility prospects, especially the electric market? How can we define clearly the competitiveness of electric driving? And what kind of impact can driving patterns and consumer behaviors have on this sector?

This paper first analyzes the technical, economical and driving parameters covered in the literature in order to address this complex issue (chap. 2). It then combines these parameters to characterize the competitiveness of electric driving from a mobility angle, thus integrating usage parameters. In addition, the notion of 'range anxiety' is also discussed. Such a combination is very rarely covered in the literature available to date.

2. Background

2.1. Electromobility at a critical step

According to Dijk et al. [6], battery and fuel cell technologies must face the increasing sales and preferences for cheaper ICE cars in emerging markets such as China, as compared with more expensive electric and hybrid vehicles that can be sold in western countries. These authors recently considered BEVs, PHEVs and FCEVs; they assert that electric mobility has crossed a critical threshold and is mainly benefitting from high oil prices and carbon constraints. Nonetheless, they still believe that doubts remain as to whether the fuel-cell technology will be ready for commercial use any time soon. Streimikiene et al. [7] performed a multi-criteria assessment of road transport technologies (BEV, PHEV and ICE with petroleum-based fuels and bio-fuels) which were ranked with respect to five emission indicators and private cost criterion. The analysis showed that the best option according to an 'equal weight' and environmental approach was renewable-based battery-electric vehicles (Re-BEVs), whereas customers would prefer biodiesel from rapeseed.

Thomas [8] viewed the situation from a different angle. He showed that there were two primary options for all-electric vehicles – batteries or fuel cells – and that fuel cells were superior to batteries for any vehicle range greater than 160 km whether in terms of mass, volume, cost, initial greenhouse gas reductions, refueling time, well-to-wheels energy efficiency using natural gas or biomass as the source, and life cycle costs. Furthermore, he believes that a major breakthrough in battery technology is required before a long-range battery EV will be able to satisfy customer needs for conventional passenger cars, particularly with respect to battery recharging times.

When Egbue and Long analyzed the barriers to the widespread adoption of electric vehicles [9], they noticed that sustainability seemed to have less weight compared with the electric vehicle cost and performance, but that the battery range was the biggest concern, followed by the cost.

When Rao and Wang [10] analyzed the development of electric vehicles, they pointed out the vulnerability of the thermal management of batteries. At stressful and abuse conditions, especially at high discharge rates and high operating or ambient temperatures, traditional thermal energy management systems for batteries (e.g. air and liquid) may not be capable meeting the

[1] Light-Duty Vehicles (LDVs) include passenger cars, light trucks, light commercial vehicles and minibuses. The truck category includes medium- and heavy-duty trucks. The bus category includes only full-sized buses. The other category includes two- and three-wheelers.

[2] Technology roadmap: electric and plug-in hybrid electric vehicles; 2011, p. 6–7 [4].

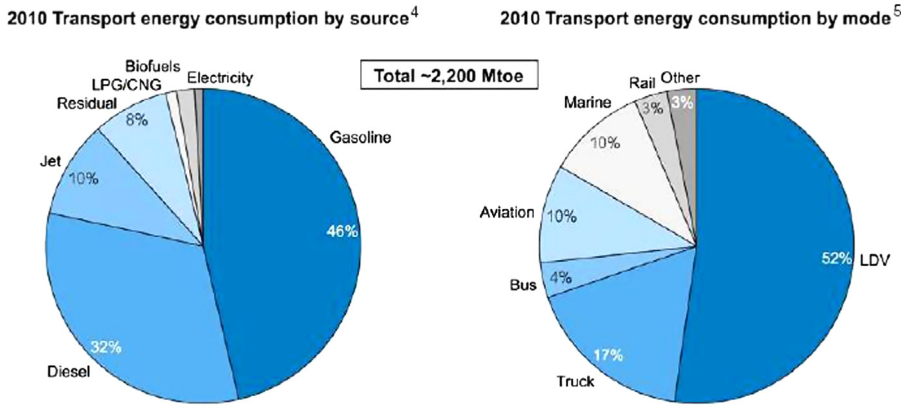

Fig. 1. Global transport energy consumption [3] (LPG: Liquid Petroleum Gas and CNG: Compressed Natural Gas).

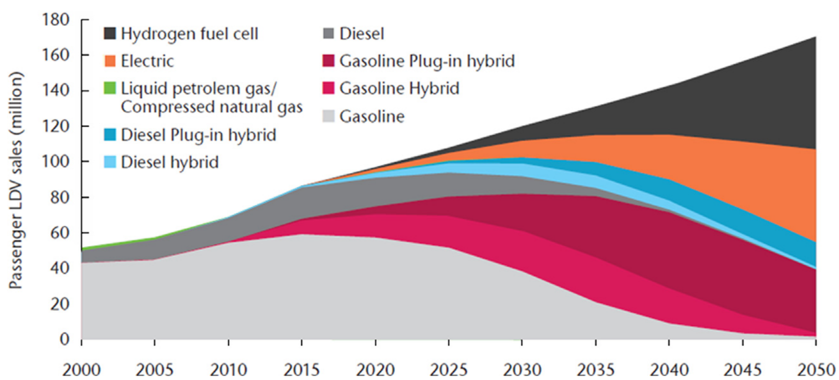

Fig. 2. Annual light-duty vehicle sales by technology/fuel type (BLUE Map scenario) [4].

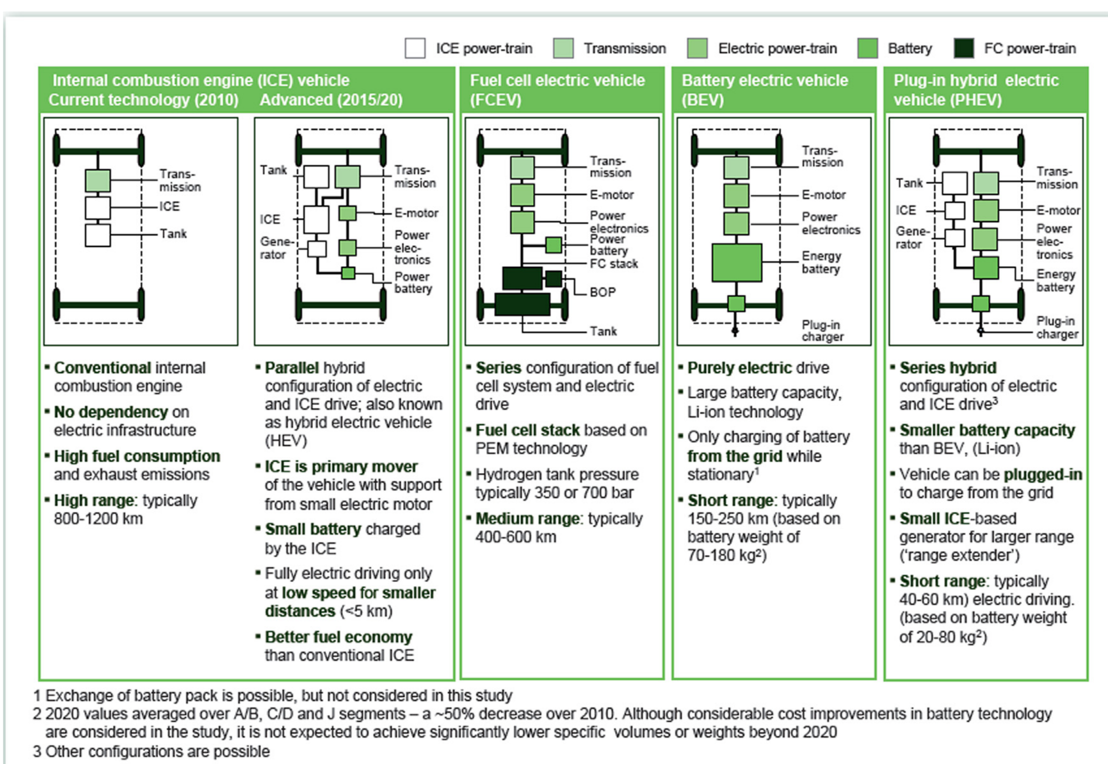

Fig. 3. Description of the following: Internal Combustion Engine (ICE) vehicle, Fuel Cell Electric Vehicle (FCEV), Battery Electric Vehicle (BEV) and Plug-in Hybrid Electric Vehicle (PHEV) [5].

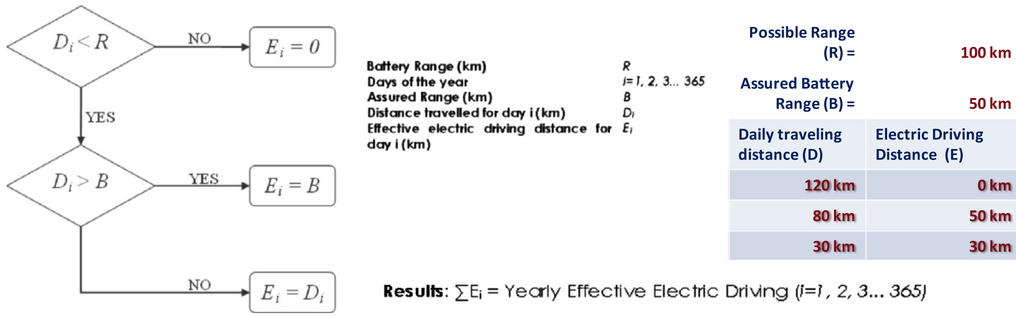

Fig. 4. Algorithm of our model used to calculate the yearly Effective Driving Distance (left). The right side of the figure gives examples for various daily traveling distances.

requirements. Nonetheless, novel and promising methods do exist, such as pulsating heat pipes and Protection Circuit Modules (PCMs).

2.2. Hybridization

Many authors highlight the advantages of hybridization to counterbalance the major drawbacks of batteries (weight, price, range and recharging time), especially when there is only one energy tank. We can cite Xu et al. [11], who combined fuel cells and batteries in a hybrid “China city bus typical cycle”; they found that the braking energy regeneration strategy (BERS) was the most efficient control strategy, which lowered hydrogen consumption by 15.3%. Barreras et al. [12] also integrated a battery pack that can be charged either from the grid or from energy produced by an onboard fuel cell system. This battery pack can therefore be used to power the vehicle, which was an innovative prototype in the field of fuel-cell powered vehicles, despite the possible drawbacks.

A few years ago, when Oltra and Saint Jean [13] analyzed the patent portfolios of Low Emission Vehicles (LEVs), they noticed that competition between the technologies and the car manufacturers was fierce, and that hybridizing appeared to be only an efficient medium-term means. In the manner of Maxton and Wormald [14], cited by [13], in the next 30 years, they concluded that the share of technologies would be characterized by a market segmentation: advanced diesel vehicles would continue to increase while FCVs, EVs and natural gas vehicles would share less than 30% of the market. Furthermore, when considering near-time markets, the study by Bradley and Frank [15] also pointed out that Plug-in Hybrid Electric Vehicles (PHEVs) offered a very efficient and simple way to replace petroleum energy with multi-source electrical energy, as well as being one of the most promising means to improve the near-term sustainability of the transportation and stationary energy sectors. Carbon emissions were significantly reduced for all the studies they cited, as well as the fact that the electrical power requirements of PHEVs can be met by the grid for even a very large infiltration of PHEVs. Moreover, they said that the real-world performance, cost, component lifetime and consumer acceptability were the real stakes of PHEV research. Bento [16], however, is less optimistic. When he addressed the issue of hydrogen car development in the market, particularly the competition with electric cars to replace conventional vehicles, he used a multi-technological competition model which shows that the early deployment of plug-in hybrid vehicles (the “*only electric technology which can compete with fuel cell cars in the multipurpose vehicle field*”) risks closing the market for hydrogen in the future. Moreover, he pointed out the importance of the starting points, particularly the early existence of a hydrogen infrastructure with sufficient coverage. According to Contestabile et al. [17], PHEVs with downsized range extenders may offer significant savings to users who are prepared to sacrifice performance, particularly top speed. Some of these authors expanded on this topic in a new paper [18] that conducted a techno-economic study on FCVs, BEVs and hydrogen Fuel-Cell plug-in Hybrid Electric Vehicles (FCHEV) in the UK using cost predictions for 2030.

Another advantage highlighted by many studies is that EVs (including PHEVs) could help the grid, particularly for the integration of renewables, i.e. use of excess energy and Vehicle-To-Grid (V2G). The publications generally say that the full environmental potential of EVs will only be realized if they are not simply used as a substitute for conventional ICE vehicles, but also as a tool for load management in the electricity grid as one component in an integrated network of different transport modes [19–22]. We need to redefine the way in which we consider mobility now that we have the chance.

2.3. Importance of real use: driving patterns, consumer behaviors and range anxiety

Though literature mostly tends to consider the technological aspects, social factors are now being analyzed more frequently. Various questions are raised, such as how does resistance to new technologies, consumer behavior or driving patterns influence the sector?

According to Green et al. in 2010 [23], if Plug-in Hybrid Electric Vehicles (PHEVs) are the next big thing in the electric transportation market, the penetration, charging characteristics, charge timing and driving patterns (consumer behavior) will have a strong influence on the distribution network nationwide. Consumer behavior was also identified as a very important criterion in the study by Faria et al. in 2012 [24]. The driving profile under different scenarios showed that aggressive driving can increase the energy consumption by 47%, as well as the use of climate control (between 24% and 60%). They showed in another publication [25] that driver behavior has a direct and large influence in the vehicle range (economic and environmental study based on experimental tests): users can adapt their driving style (e.g. by starting to decelerate sooner to avoid using the mechanical brakes, and by minimizing energy spending through smooth acceleration) and moderate their speed to maximize the distance traveled with one charge, thereby significantly reducing the cost per unit of distance traveled.

According to Dallinger and Wietschel [22], the real consumer reaction in the case of the used-load management mechanism is unclear, and the driving behavior restricts the use of this type of storage for the grid (high battery utilization and low time period available for vehicle-to-grid services). Contestabile et al. [17] compared the major powertrains and fuels that will compete in the next decades, both from technological (size, range) and cost performance (TCO analysis) viewpoints. Based on a single vehicle platform and using average driving patterns, the report showed only a few differences appear in the long term. However, with different vehicle segments and driving patterns, costs start to

diverge and certain fuel and powertrain options become more competitive than others for given market segments: BEVs are at an advantage in the smaller vehicle segments and on a low-energy driving cycle (e.g. urban and low-speed extra-urban), while FCVs and PHEVs (both FC and ICE) with relatively small batteries (i.e. 5–15 kWh) would compete head to head in the other segments of the market. The report also suggests that behavioral change should be accounted for in future comparative studies. A new paper given by some of these authors [18] included an analysis of data on distances currently traveled by private car users daily in the UK. They calculated the optimum battery sizes depending on the various uses, and pointed out that the FCHEV was considerably cheaper than the FCV mostly because of the savings from downsizing the fuel cell. Differences in behavior as a function of the vehicle size were also demonstrated, particularly the percentage of miles that can be economically driven using electricity decreases for larger vehicles.

Eppstein et al. [26] developed an agent-based model of vehicle consumers that incorporates a variety of spatial, social and media effects. Assuming there are sufficient potential early adopters, they say that providing consumers with readily accessible estimates of lifetime vehicle fuel costs could be very important for promoting PHEV market penetration. Increasing the PHEV battery range is an important leverage point and they conclude that further research is needed to determine how far PHEVs would have to penetrate the market to become acceptable to those currently more hesitant.

In short, as said by Egbue and Long who analyzed the barriers preventing the widespread adoption of electric vehicles [9], policy decisions must take into account the natural resistance to new technologies that are always considered alien or unproved, even if early adopters of EVs who are highly connected to technology already exist. Nonetheless, they need to perceive EVs to be superior in performance compared with ICEs.

In particular, the notion of '**range anxiety**' is strongly linked to the use of pure electric cars. The phenomenon of range anxiety has been discussed in the literature. Wu et al. [27] reviewed the state of the art on stationary inductive charging systems over plug-in systems. They came to the conclusion that this new technology offered the potential to circumvent battery limitation by using in-motion power transfer systems which rely on a much smaller battery size. This possible future technology may solve the inherent 'range anxiety' problem. According to Franke et al. [28], the range barrier experienced by many novices may be successfully overcome by practice in dealing with range. As a first step, a highly accessible option for users would be to simulate their daily mobility behavior, for example, using a travel diary. The opinion that range anxiety is more psychological than practical reality is shared by Thompson [29]: average electric cars, with a 50-mile range, can cover most daily driving needs without difficulty. Furthermore, the 'range extender' solution may become a common feature in the coming wave of electric cars, because it solves range anxiety in a way that is both elegant and emission-free. The Chevrolet Volt, for instance, runs for 40 miles on its batteries before a small gasoline engine under the hood is turned on to power a turbine that generates more electricity to drive the car. Even, S. Cischke, Ford's group vice president for Sustainability, Environment and Safety Engineering, told Thompson [29] that the Better Place's battery-swapping "*seems* [to be] *an interesting concept*". He said "*It solves this range-anxiety problem and it's also a way to solve this problem of battery cost*."

Pearre et al. [30] assumed that EV drivers would not change their current gasoline-fueled driving patterns and that they would only charge their electric car once a day, typically at home overnight. They showed that even with limited range, electric vehicles could provide a large fraction of transportation needs (9% of the vehicles in the sample never exceeded 100 miles in one day, while 21% never exceeded 150 miles in one day). Thus, understanding customer needs and correctly segmenting vehicle buyers by range needs, appears to be a more cost-effective way to introduce electric vehicles rather than assuming that all buyers and all drivers need currently-expensive large batteries or liquid-fuel range extenders. As regards the fast charging infrastructures, Yilmaz and Krein [31] say that they can provide a method to alleviate range anxiety for drivers of passenger EVs, while reducing onboard energy storage requirements and costs.

3. Aim and methodology

The literature discusses countless variety of ways to approach the electric driving issue. In particular, more and more papers deal with social and human aspects such as consumer behavior and driving patterns: range anxiety seems to be a major parameter in anticipating the actual entry of electric driving in the mobility market over the next few decades. It is therefore very instructive to enlighten the future competitiveness of electric driving from the mobility characteristics, in France in our case, from a quantitative point of view. Therefore, this paper considers:

- On the one hand, present and future different power train technologies to define the competitiveness limits depending on the component costs, on the progress of research and on fuel price forecasts: Internal Combustion Engine (ICEs), Hybrid Electric Vehicle (HEVs), Fuel Cell Electric Vehicle (FCEVs), Battery Electric Vehicle (BEVs) and the Plug-in Hybrid Electric Vehicle (PHEVs).
- And on the other hand, the mobility segmentation in France for an average use of LDVs. Two papers cited above [17,18] analyzed the impact of passenger cars markets and segments, together with the use patterns in the UK (range anxiety is clearly not covered). The authors say that building market segments and behavioral change into a comparative analysis could significantly affect the results and that it has to be done in future studies. This topic developed in Chapter 4 where we calculate the yearly distances that can be covered by electric driving. The techno-economic data and driving patterns are then combined to give what we believe is a more realistic approach to electric driving competitiveness.

For this purpose, a simple tool (Excel) was used to calculate the economical benefits in terms of "Difference in Total Cost of Ownership" (DTCO), according to the major TCO-influent parameters: electric driving distances, energy (fuel, electricity, hydrogen) prices, batteries and fuel cells costs, and the other major components costs. The calculation was divided into 3 steps:

- Calculation of the electric driving distances by taking into account operating parameters (e.g. battery range and range anxiety) in the assumption of recharging once a day (during the night), and according to yearly mileages and daily trip segmentation statistics. The two major assumptions described above lead to the following methodology to calculate the various effective driving distances (EDD), depending on the battery characteristics and consumer choices related to the length of daily trips (see Fig. 12). Let us consider the following example: given a battery range of 100 km and an assured range of 50 km for an EV, the driver will not use the electric mode for a 120 km trip right from the very beginning: he would choose either the gasoline vehicle to accomplish this journey or take a train thus avoiding any unnecessary trouble. The EDD in this case is 0 km. For a 80 km trip, the driver will decide to start his trip with electric driving, and the EDD value

Vehicle's name	Company	EV/PHEV	Type of battery	Battery size (kWh)	Battery range (km)	Top speed (km/h)	Launching
Kangoo be bop	Renault	EV	Li-ion	15	100	130	2011-2012
Imiev	Mitsubishi	EV	Li-ion	16	160	130	2010
Leaf	Nissan	EV	Laminate Li-ion	24	160	140	2011
Blue Car	Bolloré-Pininfaina	EV	LMP + Super capacitors	30	250	130	2010
Smart fortwo ed	Smart-Daimler	EV	Li-ion		100		2012
Th!nk city	Th!nk	EV	Li-ion (Enerdel, A123 systems)	28.3	180	100	2010
Focus BEV	Ford	EV	Li-ion	23	160		2012
Fiorina Micro Vett	Fiat/Newteon	EV	Li-ion	17 or 22	70 or 100		Already
Mini E	BMW	EV	Li-ion	35	168	153	
Ampera	Opel	PHEV	Li-ion (GM)	16	60		Production in 2011
Volvo cars.com	Volvo	PHEV	Ener1: Li-ion	11.3	50		2012
Twin Drive ecomotive	Seat	PHEV	Li-ion		50	100	Not until 2014
Prius	Toyota	PHEV			20-30		

Scenario	Average speed	Temperature	Air-conditioning	Autonomy
Ideal conditions (constant speed on flat road)	61 km/h	20 °C	No	222 km
Extra-urban driving in good weather	39 km/h	22 °C	Non	169 km
Highway in summer	89 km/h	35 °C	Yes	113 km
Home to work	79 km/h	43 °C	Yes	109 km
Trajectory in traffic jam in winter	24 km/h	-10 °C	Yes	100 km

Fig. 5. Battery data provided by major manufacturers [32] (left) and data published by Nissan for its EV LEAF™ [34] (right).

is given its assured range, 50 km, and not 80 km, which is in fact a conservative way to calculate the benefits from the EDD (for a given battery size, since the electricity cost per km is generally noticeably lower than that for gasoline). In addition, we consider that there is no range limit for PHEVs because we can always rely on gasoline to complete our travel; the EDD then corresponds to the Possible Battery Range (PBR). However, electric driving with FCEVs does not consider any daily trip segmentation or range limit, as the FCEV range is significantly higher than the BEVs range, and hydrogen refueling is feasible quickly in stations similar to the present ones for ICEs.

– Calculation of the saved fuel cost (SFC). For the DTCO, the SFC may be considered as the source of profit generated from the electricity only, during its usage lifetime. It can compensate for the higher purchasing price of EVs compared with ICEs or FCEVs. The formula for the SFC is provided below:

$$\mathrm{SFC} = \mathrm{EDD} \times (\text{ gasoline price including taxes} \\ - \text{electricity (or hydrogen) price})$$

∗ EDD refers to effective electric driving distance that is calculated in our model discussed above.
∗ SFC (€/year), EDD (km/year), and price (€/km).

– Calculation of the Difference in Total Cost of Ownership (DTCO), which is expressed in this report by subtracting the corresponding battery and power-train costs differences from the SFC. As mentioned above, the DTCO can be divided into two parts: investment costs and operating costs. In this study, the concept of DTCO actually considers BEVs:

$$\begin{aligned}\mathrm{DTCO} &= \text{Saved Fuel Cost} - \text{Surcharge of the battery and} \\ &\quad \text{powertrainSurcharge of the battery and powertrain} \\ &= \text{battery range (km)} \times \text{unit battery cost (\$/kWh)} \\ &\quad /\text{battery performance (km/kWh)} - \text{cost difference of} \\ &\quad \text{powertrains} = \text{battery range (km)} \\ &\quad \times \text{unit battery cost (€/kWh or €/kW)/4.8} \\ &\quad \text{(km/kWh)} - \text{(ICE powertraincost} \\ &\quad - \text{electricpowertraincost)}\end{aligned}$$

From the formula above, we can see that the DTCO represents the price gap between electrified vehicles and conventional vehicles. For example, if the DTCO equals 0, it means that there are no differences between conventional vehicles and electrified vehicles. If DTCO is negative, it means that the usage of electrified vehicles is more expensive than that of conventional vehicles. If the DTCO is positive, it means that we can take advantage of using electrified vehicles.

4. Consumers driving characteristics

BEVs are disadvantaged by their limited range (the McKinsey analysis [5] gives a maximum range value ca. 200 km in 2050), but can really benefit from mobility habits. Supporters of the electric vehicle argue that its poor range is not a disadvantage; they insist on the fact that most daily trips cover short distances. A recent IEA report [4] indicates that in the United Kingdom, 97% of all trips are estimated to be shorter than 80 km. In Europe, 50% of all trips are shorter than 10 km and 80% of all trips are shorter than 25 km. In the United States, about 60% of all vehicles are driven less than 50 km daily and about 85% are driven less than 100 km [4].

Two important assumptions have therefore been made to assess Electric Driving Distances that could really be covered in France with regards both consumer needs and battery capabilities.

The first assumption concerns the effective battery range vs. the range value given by suppliers (Fig. 5 [32]). Published technical data is often too optimistic to be considered reliable; there is always a range anxiety. The range anxiety is the fear that a vehicle has insufficient range to reach its destination and will strand the vehicle's occupants [33]. Due to preliminary feedback from PSA Peugeot Citroën [34], the range of the electric vehicle called Ion – equivalent to 140 km according to standardized tests – was very sensitive to certain driving conditions which meant that its range could decline to 70 km. Nissan's EV LEAF also shows a factor 2 between the maximum and minimum battery range according to different driving conditions ([34], Fig. 5).

This report therefore defines the Assured Battery Range as the range anxiety limit or the minimum capacity of a battery, while the Possible Battery Range is defined as the maximum capacity of the battery or announced battery range. There is roughly a factor 2 between them: ABR = 0.5 × PBR.

The second assumption considers that EVs and PHEVs are rechargeable only once a day, mainly during the night. The French Development Plan for Recharge Stations [35] says that a significant number of electric plugs will be installed by 2020 on public roads and parking lots. But the report by CAS 2011 [34] says that 90% of all recharging should be done at home at night. Feedback from the pilot project VHR Strasbourg EDF [36] also shows that users of Hybrid Electric Vehicles recharge their vehicle 0.9 times a day on average. Therefore, this assumption seems quite relevant.

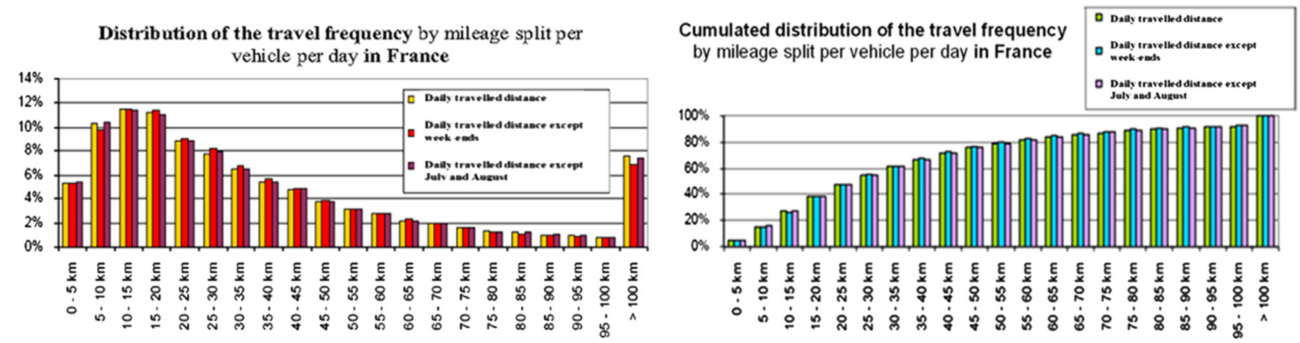

Fig. 6. Distribution and cumulated distribution of the travel frequency by mileage split per vehicle per day [37].

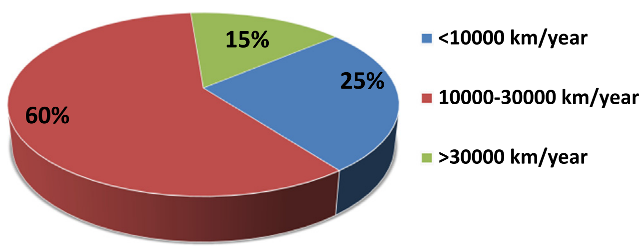

Fig. 7. Distribution of personal vehicles according to the split km per year [39].

Fig. 6 gives the daily mobility characteristics in France based on the ENTD[3] 2008 database [37] which recorded the distances traveled each time (from start to finish) in a day for a whole week. Only passenger vehicles and Light Duty Vehicles (LDVs) were investigated and the statistics were based on a sample of 10,179 vehicles. The distances registered are those driven on the road. A total of 40,518 observations were processed by the Odomatrix software. Fig. 6 shows that ca. 92% of daily traveling is shorter than 100 km, which means that a 100 km range battery could satisfy 92% all the daily trips. According to the data on average distances per trip (10.3 km) and average numbers of trips per day (2.04), the average distance traveled per day is 21 km. When accumulated, it comes to an occurrence of 80% for a daily driving distance shorter than 55 km. A battery with a 40 km range could cover 67% of all daily trips.

Fig. 6 gives the distribution of personal vehicle trips, but it could be also interpreted as the probability of occurrence of variable driving distances per day and per vehicle. The annual traveling distance can then be calculated based on the assumption of homogeneous driving behaviors, i.e. about 15,500 km. This figure is coherent with the data provided by several organizations, national questionnaires and statistical analysis in France that describe the variation in the annual average mileage of personal vehicles (Girault [38]: between 12,000 km/yr and 15,000 km/yr between 1976 and 1999, with a 2% increase in the annual driving distance per year).

A 2005 inquiry in France [39] showed that the contribution of vehicles driven between 10,000 and 30,000 accounted for 70% (Fig. 7). This contribution has remained the same up to now, as shown by the *Compte Transports* analysis [40] which gives the 2010 statistical distribution of the yearly mileages: 11 segments between 0 and 50,000 km/yr, one segment for yearly mileages over this value.

This data nevertheless needs to be put into perspective. Even if 92% of all daily traveling is shorter than 100 km in France, the whole distance traveled more than 100 km length remains significant: ca. 35% of the yearly mileage [37]. The average “long distance trip” (over 100 km/day) is ca. 265 km.

[3] French national inquiry on transportation and travel habits in France.

As Fig. 7 describes the distribution of the travel frequency for the average yearly mileage (15,500 km/yr) and as we do not have data for the daily travels segmentations of other yearly mileages, a new distribution of the travel frequency per split km could be calculated when given another yearly distance by using a bottom-up method. For this purpose, we assumed homogenous driving behaviors for different vehicles and multiplied each split km by a coefficient obtained by dividing the given annual distance by 15,500. This homothetic transformation assumption gives the distribution of split kilometers for each yearly distance segment. Of course real segmentations market per market and with the corresponding statistics will be necessary for further studies.

5. Estimation of yearly Effective Driving Distances (EDD)

The evaluations of effective Electric Driving Distances (EDD) will give the possible BEV and PHEV contributions to traveled distances. In past studies, usually very rough estimations or assumptions were made with relation to the EDD, which could lead to misleading results. For example, in the report of McKinsey & Company [5], it seems that a 12,000 km annual driving distance is supposed to be adapted to both electric vehicles and internal combustion vehicles. In the CGDD report [37], the EDD of electric vehicles is considered as equal to that of gasoline vehicles (13,000 km/yr). This supposes both sufficient range and electricity network with fast battery charging devices. And for PHEVs, 50% of the total distances are considered as EDD while the remaining 50% are considered to be assumed by gasoline. This paper considers consumer driving characteristics and the corresponding assumptions, as described above (chapter 3), to calculate the EDD.

Fig. 8 shows simple applications of the EDD calculation model by considering real model vehicles: Toyota Prius PHEV and Renault Fluence BEV. The results give the annual kilometers that are accessible to electric driving (blue bar), which is qualified as Potential Zero Emission Mode (PZEM) driving, depending on the yearly mileages (yellow bar). The Toyota PHEV Prius has an assured battery range of about 20 km and can undertake a trip of up to 475 km when factoring in the range of gasoline driving. The assured battery range of the Renault Fluence is set as 100 km and its battery range limit is set as 185 km according to the official data ([32], [41]).

As regards the Renault Fluence BEV, the results show a very interesting proportion of PZEM in the split km for 78% of all French vehicles, i.e. those driven less than 30,000 km (14): 60% to 70% between 10,000 and 30,000 km/yr, and up to 100% for vehicles driven up to 5,000 km/yr, given our split km assumptions. From 30,000 km/yr upwards, the electric mode driving remains almost the same and quite significative (one third or more of the yearly kilometers).

The proportion of the potential zero emission modes (pure electric driving mode) decreases strongly with the increase in the annual traveled kilometers for the Toyota Prius PHEV. In this case,

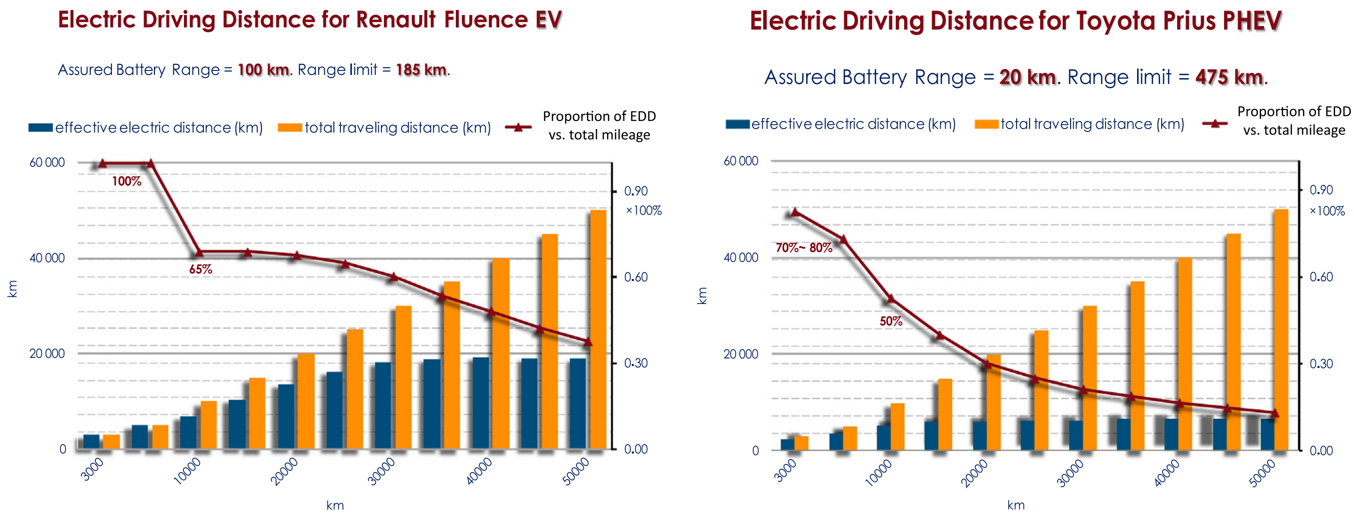

Fig. 8. EDDs calculations for the Renault Fluence BEV (left) and the Toyota Prius PHEV (right).

Fuel cost (€/km) With gasoline tax	2010	2020	2030
ICE	0.08	0.06	0.06
BEV	0.03	0.03	0.03

Source: réf. (5)

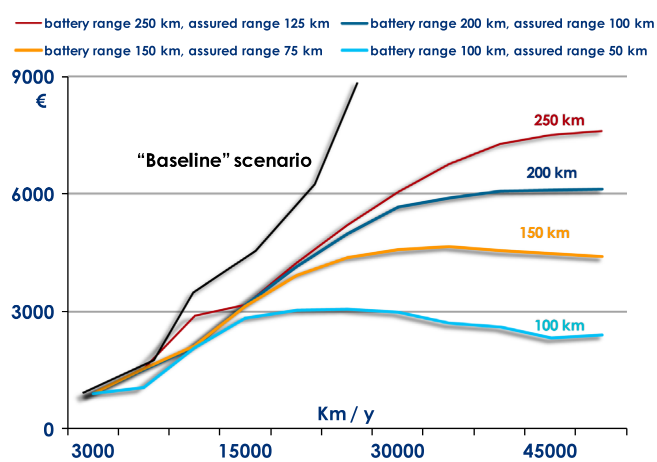

Fig. 9. Fuels' costs assumptions and influence of the battery range on SFC for 2010–2020.

however, the range anxiety is not considered since the ICE takes over the electric drive where necessary and the assumption is then that the first kilometers are always electric. Nevertheless, the PZEM reaches high values at low annual mileages (up to 40% for 15,000 km/yr), which is the average annual traveling distance in France, even for very limited battery ranges (20 km). It shows the significant impact of the cumulated kilometers of short trips that can be covered even by short-range batteries, as well as by considering daily mileages (no recharge during a whole day, even at work).

Moreover, when the algorithm (Fig. 4) supposes range anxiety, i.e. for distances over the possible range, no electric driving is considered for the first kilometers, which lowers the EDD. Whenever electric driving is considered from the first kilometer (e.g. for PHEVs), this increases the EDD's rate roughly by 5% to 15%.

6. Difference in Total Costs of Ownership (DTCO)

This section analyzes the DTCO gaps between different powertrains vehicles: ICE, BEV, PHEV and FCEV. The economical benefits in terms of DTCO are discussed according to the major TCO-influent parameters: electric driving distances, energy (fuel, electricity, hydrogen) prices, batteries and fuel cells costs.

In this paper, we consider an exchange rate €/$ = 1.4 (when literature data are given in $).

6.1. Comparisons between BEVs, PHEVs and ICEs

6.1.1. Saved Fuel Costs (SFC)

The first step, described here, is the calculation of the saved fuel costs (differences in the operating costs) which is needed to highlight the specific impact of EDDs and the investments costs (vehicle purchases). Chapter 3 recommends a method to assess the effective Electric Driving Distance (EDD) which is an essential parameter in the calculation of the DTCO. EDD assessments provide quick access to the relative Saved Fuel Cost (SFC) of hydrogen (or electricity) per year compared with conventional gasoline driving.

We consider here that the gasoline price includes taxes, i.e. at the pump, because the overall competitiveness has to be assessed by consumers. Therefore, electricity (or hydrogen) prices are also considered 'at the pump' (or at the plug for electricity).

Only the SFC of BEVs vs. ICEs is analyzed as it implies the EDD characteristics described above. The competitiveness analysis of FCEVs vs. ICE does not require EDD data and is developed later.

The yearly SFC is calculated first and then the 10-year SFC is calculated using a yearly discounted rate of 5% to show the present lump-sum amount. As fuel costs evolve, we consider a scenario that takes into account electricity and gasoline cost changes every year over the 10-year period (linear variations from data given by [5]). Fig. 9 gives the possible SFC for the next decade by using electricity instead

of gasoline (energy and fuel price assumptions for a vehicle cat C/D [5]), depending on the different battery ranges.

This figure clearly shows that consideration of the EDD has a noticeable impact on the SFC that can be assessed without using the data in Fig. 6 and the algorithm in Fig. 4. From 20,000/30,000 km, the SFC remains almost the same (more kilometers driven with gasoline).

It can also be seen that for all battery ranges (100 km to 250 km), the SFC shows no great differences before the split km under 15,000 km/yr, which represents 40% of all vehicles [40]. As expected, considerable differences appear for longer yearly trips, which benefit the larger battery ranges, while some of them are not negligible (over €6000).

6.1.2. Difference in Total Cost of Ownership (DTCO)

Recent studies suggest that the Total Cost of Ownership (TCO) will become a more useful metric for private-consumer-comparing vehicles [42,43], than the current focus on fuel prices only [44,45] which no longer reflects reality since a great deal of R&D is focusing on fuel cells, hydrogen tanks and batteries.

We consider the following assumptions for ICE and BEV engine costs:

- EV unit battery cost is considered to be €215/kWh on average during 2010–2020: the target price of the US Department of Energy [46] is to reduce 70% of the battery pack cost from €715/kWh in 2009 to €215/kWh by 2015. In a recent report, however, the latest electric vehicle of Nissan-LEAF's battery pack costs just €270/kWh [47] which almost reaches the US objective (€215/kWh) for 2015.
- Battery performance: 4.8 km/kWh (as proposed by [46]).
- ICE power train and Electric power-train costs are given by Offer et al. [48].
- Lifetime usage of 10 years and a discount rate of 5%.
- No government subsidies are considered here.
- For battery ranges set as 250 km, 200 km, 150 km and 100 km, assured range = 0.5 × battery range.

Other car components costs and operating characteristics costs (passengers' compartments and facilities, maintenance, insurance) are considered similar. Fig. 10 gives the results for various battery ranges depending on the yearly mileages (3000 to 50,000 km/yr) and battery lifetimes (10 years and 5 years).

Fig. 10 shows that for a ten-year lifetime battery and under the French kilometer segmentation data and assumptions, the 100 km range battery gives the best profitability. Over 35,000 km/yr, there is almost no difference between all the battery ranges considered. Real differences appear if the battery lifetime is 5 years instead of 10: negative DTCOs between twice and four times the 10-year lifetime values, for low and high yearly mileages respectively. In this case, the battery has to be changed once, which generates a battery surcharge after 5 years; then:

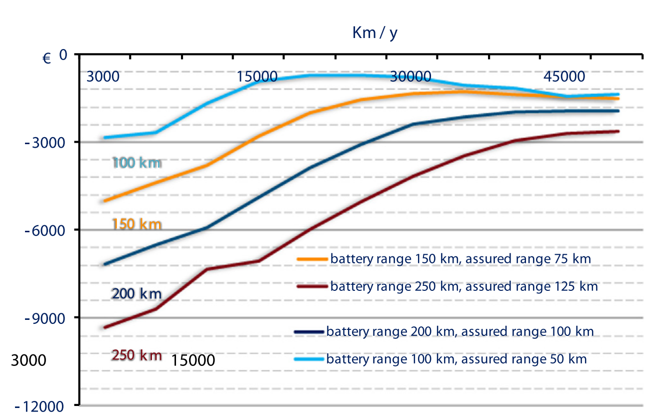

Fig. 10. DTCO between BEVs and ICEs for various battery ranges (battery lifetime of 10 years) according to the yearly mileage.

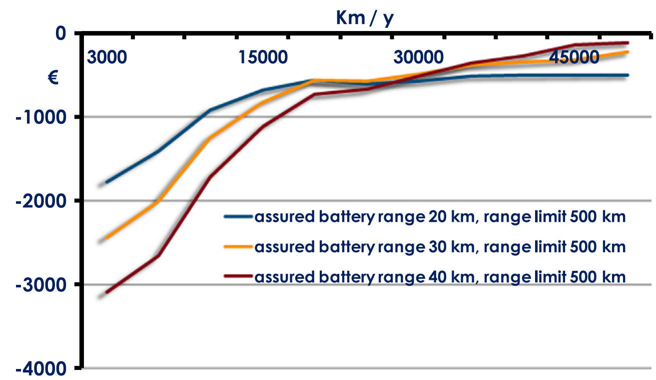

Fig. 11. DTCO between PHEVs and ICEs for various battery ranges according to the yearly mileage (battery costs: €360/kWh).

Input battery cost for the case of a 5-year battery lifetime = Coefficient × battery cost for the case of 10-year battery lifetime and Coefficient = $1+1/(1+i)^5$, if $i=5\%$ then coefficient = 1.78..

The figure shows that the battery related expenditure is 1.78 higher after considering a battery lifecycle of 5 years rather than 10 years. DTCO differences remain important for mileages over 35,000 km/yr and important losses also arise which are difficult to offset. Generally speaking, the search for long-range batteries may not be the priority, at least in the case of a €215/kWh battery cost (2020 target [5]).

This argument also applies to any other expenditure (power-train costs, insurance, end-life value, etc.) that may arise for electric and/or ICE cars, by applying the appropriate discount value similar to the 5-year battery lifetime case. This leads to translations of the curves, up or down whether it is to the benefit of electric driving or not.

Concerning PHEVs vs. ICEs, there is no surcharge for ICEs when ICE powertrains exist in both vehicles. Fig. 11 shows the results for PHEVs with short battery ranges (ca. Plug-In Hybrid Prius), then with no range-anxiety consideration (electric drive anytime from the first kilometer). Other expenditures remain, but they are much lower and minor for yearly mileages over 20,000 km/yr.

It is important to highlight the impact of the battery cost: in the particular case of the PHEV, electric driving is profitable when the mileage is over 15,000 km/yr and the battery cost is ca. €215/kWh, an objective that seems quite achievable.

Fig. 12 shows the impact of various battery costs. The left side of the figure shows that if the battery cost is half the price of that considered in Fig. 11, €110/kWh vs. €215/kWh in this case), it can lead to DTCO profits, particularly for high yearly mileages. Differences persist between the various battery ranges but they are much less significant.

On the right side of the figure, if we compare the present cost performance of the batteries[4] with the 2020 target average cost,[5] the DTCO gap for a 150 km battery range vehicle and an ICE vehicle is roughly €0.15/km. It is higher than to the fuel cost of the vehicle, ca. €0.1/km, for the average French yearly mileages (15,000 km/yr).

In addition, the variation in the electricity price shows a minor impact. All this highlights the importance of the battery costs and

[4] Roughly €700/kWh which is roughly 1000 \$/kWh (exchange rate €/\$ = 1.4). Ref. [5] gives an average value of €871/kWh in 2010.

[5] €300/kWh [5] – ca. \$400/kWh.

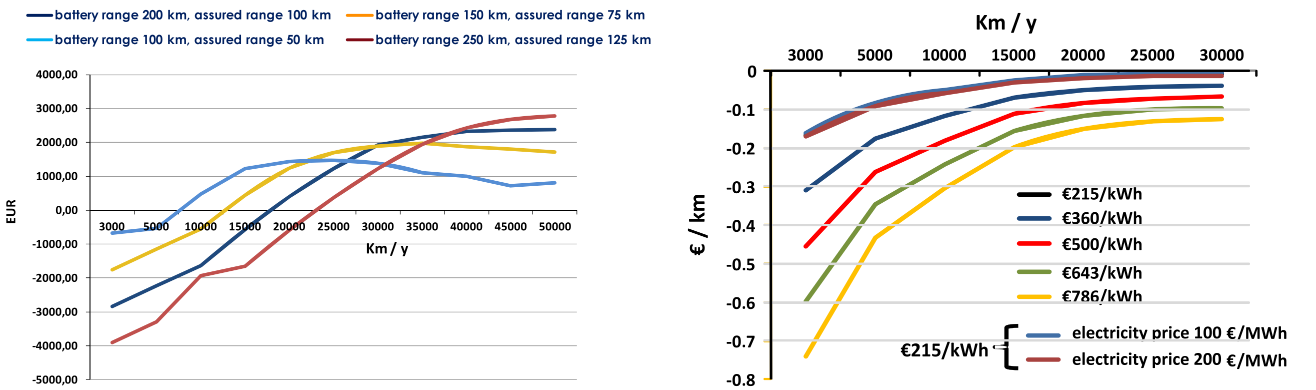

Fig. 12. Impact of the battery cost (€110/kWh instead of €215/kWh) for various battery ranges (left, expressed in €) and of various battery costs for a 150 km battery range (right, expressed in €/km) relative to the DTCO.

can be an interesting guiding principle to evaluate the incentives that could promote electric driving. Fig. 10 above shows that the DTCOs brackets fall within the same order of magnitude as the present incentives given by the French government, i.e. €5000 for vehicles producing less than 60 g CO_2/km [44], as well as the American policy for vehicle subsidies. For vehicles acquired after December 31, 2009, the credit is equal to €1786 ($2500) or more, whereas for a vehicle which draws propulsion energy from a battery with at least 5 kWh of capacity, the credit amounts to €300 ($417) plus an additional €300 ($417) for each kilowatt hour of battery capacity in excess of 5 kWh. The total amount of credit for a vehicle is limited to €5360 ($7500, [45]).

6.2. Comparisons between FCEVs and ICEs

This section compares two power train technologies to define the competitiveness limits which depend both on the components and the energy costs: Internal Combustion Engines (ICE) and Fuel Cell Electric Vehicles (FCEV). Electric driving with FCEVs does not consider any daily trip segmentation or range limit, as FCEV ranges are significantly higher than BEV ranges, and hydrogen refueling is feasible quickly in stations similar to the present ones. Comparisons between ICE and FCEV technologies are based on DTCO calculations. Furthermore, as investment costs may strongly differ (ICE vs. FCEV power-trains, FCs, hydrogen tank purchases), contradictory results can be obtained depending on the assumptions and R&D progress forecasts. Instead of directly comparing the economical differences between the two power-train usages (investments and operating costs), the *hydrogen target costs* are provided in relation to other parameters, mainly the FC cost (€/kW).

6.2.1. Saved Fuel Costs (SFC)

The first step is to calculate the saved fuel costs (differences in the operating costs) in order to clearly highlight the specific impact of the investments costs (vehicle purchases) later. Relative to the DTCO, the SFC may be considered as the source of profit generated from only using the vehicle during its usage lifetime and can compensate the higher purchasing price of FCEVs vs. ICEs. The very simple SFC formula is provided below:

$$\text{SFC} = \text{gasoline price (including taxes)} - \text{hydrogen price}$$

In the same way as the comparisons between battery electric and ICE driving, the yearly SFC is first calculated and then the 10-year SFC is determined by a yearly discounted rate of 5% to show the present lump-sum amount. As fuel costs evolve, we considered a scenario that takes into account the hydrogen and gasoline costs changes every year over a ten-year period (linear variations from data given by McKinsey & Company [5]).

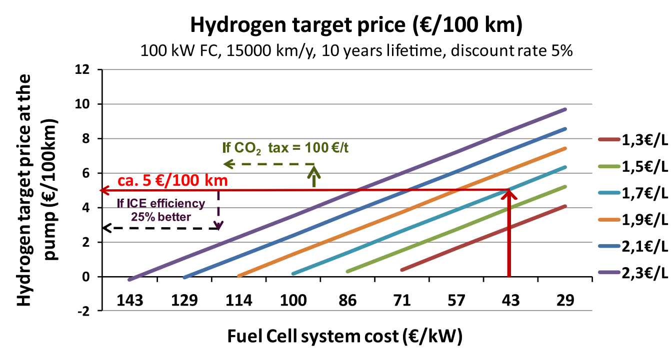

Fig. 13. H_2 target prices vs. FC costs relative to the fuel price at the pump for a similar ICE/impact of CO_2 taxation and gain on ICE efficiency.

6.2.2. Difference in Total Cost of Ownership (DTCO)

Hydrogen is one of the alternative transport fuels expected to replace conventional oil-based fuels. The paper finds that it is possible for non-fossil-based hydrogen to become the cheapest fuel without favorable tax treatment. The order of per kilometer cost depends on performance in hydrogen production, the international oil price and fuel taxes. The DTCO is expressed by subtracting the corresponding costs of fuel cells and powertrains from the SFC. As we do not need to consider EDDs in this specific case, we can determine the hydrogen target price through DTCO comparisons between FCEVs and ICEs:

$$\begin{aligned}\text{DTCO} &= \text{Saved Fuel Cost} - \text{Surcharge of the}\\ &\quad \text{Fuel Cell and Powertrains}\\ &\quad \text{Surcharge of the Fuel Cell and Powertrains}\\ &= \text{unit Fuel Cell cost } (\text{€}/\text{kW}) \times \text{Fuel Cell power (kW)}\\ &\quad - \text{cost difference of powertrains (ICEpowertraincost}\\ &\quad - \text{electricpowertraincost)}\end{aligned}$$

From the formula above, the DTCO represents the price gap between the FCEV and the conventional ICE vehicle. For example, if the DTCO equals 0, it means that there are no differences between conventional vehicles and electric Fuel Cell vehicles. If the DTCO is negative, it means that the usage of FCEVs is more expensive than that of conventional vehicles. If the DTCO is positive, it means that we can take advantage of using FCEVs.

The hydrogen target price is therefore given through the DTCO comparisons between FCEVs and ICEs, under certain assumptions:

- ICE power train, Electric power-train and FC tank costs are given by [46]: respectively €1710 ($2400), €1143 ($1600) and €1430 ($2000).
- Life time usage of 10 years and a discount rate of 5%.

- A fuel cell of 100 kW.
- An annual distance of 15,000 km/yr (average for France).
- No government subsidy is considered here.

Fig. 13 gives the H2 target prices vs. FC costs relative to the fuel price at the pump for a similar ICE.

Fig. 13 shows the very strong impact of the fuel cell cost on the H_2 target price, at the pump, for a given ICE fuel price. From this figure, the DTCO of a 100 kW FCEV with a fuel cell cost of $60/kW[6] will be the same as that for a similar ICE car which uses 5.6 l/100 km if the ICE fuel and FCEV hydrogen costs are €1.7/liter and ca. €5/100 km at the pump respectively (€5/kg H_2 for 1 kg H_2/100 km). The most important thing may be the slopes of the fuel prices lines: if the FC cost is €100/kW for the same €1.7/liter of gasoline, the hydrogen price at the pump would have to be 0 €/kg to achieve the same operational cost as gasoline. This highlights the importance the R&D on hydrogen Fuel Cells.

Reducing the cost of fuel cells greatly depends on the economies of scale; the US Department of Energy [49] has already fixed a fuel cell target price of $30/kW (€20/kW) by 2015. Under this assumption and with a gasoline price of €1.7/liter, the hydrogen price should be less than €6.5/kg, an objective that seems achievable. Nevertheless, these values noticeably depend on the car size, the yearly distance driven, the lifetime, and discount rate considered, not to mention the possibility of taxes that could be established. In France, the average fuel (diesel and gasoline) price at the pump in 2011 was ca. €1.4/liter, roughly a half for the w/o tax price (Brent+refining+distribution) and a half for the taxes [50]. Therefore, for an ICE vehicle that runs 100 km and uses 5.6 l/100 km, the overall tax is ca. €4/100 km which is a significant revenue for the Government. However, the foreign trade deficit will be lower if hydrogen is a national product, which is an important issue for the economy. In any case, prices in the range €5–€7/kg are close to the values cited in the McKinsey analysis [5] from 2030 (production mix+transport+delivery). However, after the investment peak devoted to the infrastructure, this could prove difficult to achieve if hydrogen is produced by renewables such as wind energy: production costs could fall in the range €9–€18/kg for isolated systems depending on the supply constraints [51].

Moreover, Fig. 13 illustrates the impact of a CO_2 tax for vehicles: €100/tCO_2 is the value advocated by the CAS in France in 2030 [52]. Hansen et al. [53] noticed the impact of fuel taxes: hydrogen mobility seems to be competitive when the barrel price reaches $125, whereas the threshold price decreases to $80–90/bbl when fuel and CO2 taxes are applied. In our case, if ICE vehicles are subjected to a €100/tCO_2 tax, there will be an increase of roughly €1/kg H_2 at the pump, which is not negligible. But an increase in the ICE efficiency corresponding, for instance, to 25% less consumption[7] leads to a significant contradictory effect of about €2/kg H_2 at the pump.

It is therefore very likely that specific mobility markets could take advantage of developing FCEVs.

7. Conclusion

This paper compares different powertrain technologies in terms of ICEs, BEVs, HPEVs and FCEVs.[8] The economical benefits in terms of the Difference in Total Cost of Ownership (DTCO) are discussed according to the major TCO-influent parameters: electric driving distances, energy (fuel, electricity, hydrogen) prices, batteries and fuel cells costs. Electric driving distances were simulated using a model that takes into account the French daily trip segmentation statistics and functional parameters (e.g. battery range and range anxiety) in the assumption of recharging once a day (during the night). The results also provide the relative impact of the yearly mileages and show important ratios of electric driving potential, both for BEVs (60% to 70% between 10,000 and 30,000 km/yr, up to 100% for vehicles driven up to 5000 km/yr) and PHEVs (up to 40% for 15,000 km/yr, which is the average annual traveling distance in France), even for a very limited battery range (20 km).

The DTCO calculations show the importance the battery costs (competitiveness under $300/kWh, for instance $150/kWh) and lifetimes on the one hand, and the fact that lower battery ranges (100 km in our case) lead to the best profitability factors on the other hand. Range anxiety is not considered for PHEVs, and $300/kWh for BEVs can render short-range batteries profitable under our assumptions.

As regards FCEVs, with reasonable gasoline prices (€1.7/liter at the pump) and fuel cell costs (€20/kW–$30/kW by 2015 as planned by the US DoE), the hydrogen price should be below €6.5/kg, an objective that seems achievable. Nonetheless, CO_2 taxes and/or ICE efficiency gains will lead to visible and contradictory impacts of the H_2 target prices at the pump. H_2 competitiveness at the pump will also strongly depend on the taxes.

[6] ca. €43/kW, 2020 average FC cost given by the recent European analysis [5].

[7] The McKinsey analysis gives 30% in 2050 [5].

[8] Internal combustion engines, electric vehicles, hybrid electric vehicles (plug-in), and fuel cell electric vehicles respectively.

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